INSTRUMENTS

# Measure Resistances with Six Wires

Martin Rowe
*Senior Technical Editor*

To measure the value of a single resistor that's not installed in a circuit, you just connect the resistor to a DMM and measure the resistance. But what if you can't separate the resistor from its circuit? That's the problem manufacturers of resistor networks, sensors, and connectors face. Line-termination networks, for example, have resistors in parallel that combine to produce wrong measurements.

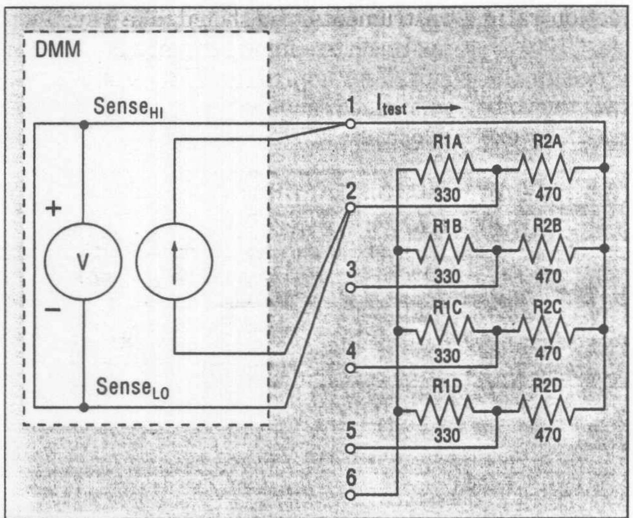


**FIGURE 1** The DMM can't measure *R2A* unless you remove the resistor from the circuit.

In some circuits, resistors are connected across protection diodes, which also alter measurements.

If you're trying to measure the resistance in a section of a PCB trace, you may find a trace that has other traces connected to it. To measure resistance, you have two choices: You can cut the trace and connect your DMM to the resistor, or you can use the six-wire method, called "guarding," to isolate the unknown resistance from the rest of the circuit. The six-wire method requires at least two series resistors in parallel with the unknown resistance.

In **Figure 1**, you can't use a four-wire DMM to measure the value of *R2A* without disconnecting the resistor from the network. If you connect a DMM's source and sense leads to pins 1 and 2 of the resistor network, you'll measure *R2A* in parallel with three sets of resistors, which calculates to 597 Ω in parallel with *R2A*. That's an equivalent resistance of 262 Ω. If you could force the current in *R1A* to zero, however, then all of $I_{test}$ could flow through *R2A* and no current would flow through the other resistors (*R1B* to *R2D*). You'd get the correct reading.

### Six from Four

**Figure 2** shows that adding an op amp and two wires to a four-wire resistance measurement produces a six-wire measurement. Resistor *R2A* is the resistor under test. $R_{eq}$ represents the equivalent value of the parallel resistor pairs in the network—*R1B* through *R2D* in Figure 1 (597 Ω). The op amp, configured as a voltage follower, forces the voltage across $R_{eq}$ to nearly zero. Therefore, most of $I_{test}$ should flow through *R2A*.

A simple and elegant solution? Well, almost. No op amp is perfect, so it can always introduce errors. Manufacturers of DMMs with six-wire ohms measurement capabilities have to add circuits to compensate for those errors.

The op amp's offset voltage, $V_{OS}$, contributes to measurement errors. That voltage, typically in microvolts, will cause some current to flow through *R2A*, which affects $I_{test}$.

Assume that each "*R1*" resistor in the network is 330 Ω nominal and each "*R2*" resistor is 470 Ω nominal. The value of

$R_{eq}$ is (330+470)/3 or 267 Ω. If $V_{OS}$ is 20 μV and $I_{test}$ is 1 mA, then the error caused by $V_{OS}$ and $R_{eq}$ is: $Error\ (\%) = (V_{OS}/(R_{eq} * I_{test}))*100$, which is 0.0075%.

A 0.0075% error doesn't seem like much, but if you're measuring the resistance of a PCB trace, then $R_A$ can reduce to less than 1 Ω, which increases the error significantly. As $R_A$ approaches zero, the error it contributes approaches infinity. So, you can't use the six-wire method to measure a resistance unless the unknown resistor has at least two series resistances in parallel with it.

The op amp must also supply enough current through *R1A* so the voltage across *R1A* equals the voltage across *R2A*. To further reduce errors, the DMM manufacturers will automatically adjust $V_{OS}$ closer to 0 V.

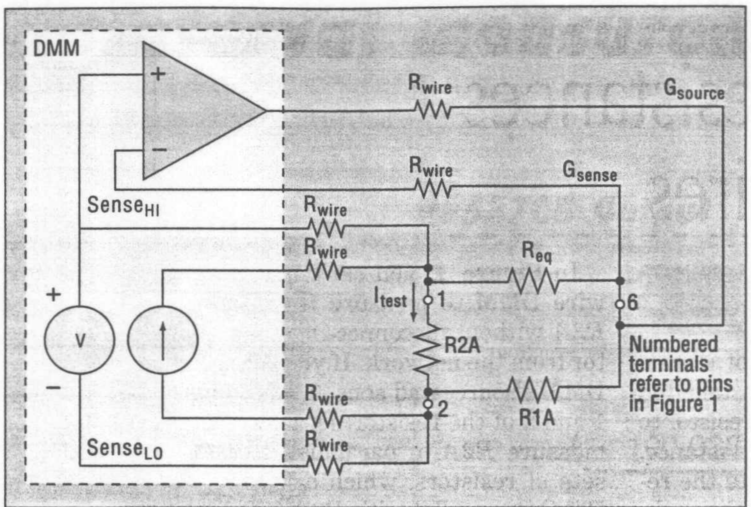


FIGURE 2 The op-amp forces little or no current to flow though $R_{eq}$ so all of $I_{test}$ flows through *R2A*.

Common-mode voltages contribute to measurement errors, too. Meter designers prefer op amps with as high a common-mode rejection ratio (CMRR) as possible—at least 100 dB.

Manufacturers may also design the op amp's power supply to track the voltage at the $Sense_{HI}$ connection. If, for example, the voltage at $Sense_{HI}$ is 5 V and the op amp's power supply covers a range of 30 V, then the meter will adjust the op amp's power supply to +20 V and –10V, rather than leaving it at ±15 V. Adjusting the power supply keeps the op amp's input voltage relative to the power-supply rails, which minimizes errors caused by common-mode voltages at the op amp's output.

Can you simply add an op amp to your four-wire DMM to obtain the six-wire guarding capability? You can, but you must know how much measurement error you can tolerate. According to Chuck Cimino at Keithley Instruments, you should take a system approach to adding your own guard circuit. Your approach will depend on the resistance range you want to measure, which also affects the amount of $I_{test}$ you

current that the op amp must supply.

You'll need an op amp with a high input impedance, typically in the gigohms range. To minimize errors, you also should look for an op amp with the lowest possible input bias current. Remember, any current that flows into the op amp will change the value of $I_{test}$. The into greater errors for a given amount of bias current.

You'll also need to minimize $V_{OS}$, which you can do with a potentiometer connected to the op amp's offset-compensation pins (not shown in Fig. 2). Using a manual offset adjustment is fine for lab work. For production, where you the offset compensation frequently, perhaps every day depending on the accuracy you need. An op amp's $V_{OS}$ can slowly drift because the device self-heats, particularly as the guard current $G_{source}$ nears the op amp's maximum current output. According to Tee Sheffer, president of Signametrics (Seattle, WA), the greater an op amp's output current, the greater its $V_{OS}$, so you may trade one error source for another.

Choose an op amp with as high a common-mode rejection ratio (CMRR) as possible. Otherwise, the op amp's CMRR will contribute an error that may exceed the error caused by $V_{OS}$.

You may not find an op amp that has the spec for every characteristic that affects your measurements. Still, by calculating the amount of error you can tolerate, you can select an op amp that adequately meets your needs.

If you need to measure in-circuit resistors in production or incoming inspection, you can add switches to your test setup to measure various resistances or those in several circuits at once. But you must account for additional errors from the switches and cables. According to Sheffer, thermal EMF voltages across the switches can add significant errors depending on the resistor values in your device under test.

You may also need several feet of cable between your DMM and devices under test. In these situations, IR voltages in the cables and thermal EMF voltages—as high as 300 $\mu$V—across the switches can introduce measurement errors. To minimize these errors, connect $G_{sense}$ and $G_{source}$ as close to the DUT as possible. If you're making measurements in the lab with short cables and no switches, then you can connect $G_{sense}$ to $G_{source}$ at the meter. Use copper wire to minimize thermocouple EMFs caused by the junction of dissimilar metals. *T&MW*

## FOOTNOTE

1. Schwertner, Thomas, *Obtaining More Accurate Resistance Measurements Using the 6-Wire Ohms Technique*, Keithley Instruments, Cleveland, OH, *www.keithley.com/white_papers/schwertner/sixohms.html*.

*You can contact Martin Rowe at mrowe@cahners.com*